

Single Rotor Turbine Engine Proof of Concept

Subcontract No. 04550-001-04 4X

Phase Two Review and Final Report

December 3, 2004

AGENDA

- Objectives and Approach for Phase II Activities
- Attractive SRT Enabled Applications
- Bench Marking - Competitive Engines
- Baseline SRT Enabled Applications -
 - Baseline Engine Cycle Selection
 - Turbomachinery Flowpath Geometry
 - Mechanical Arrangement
 - Review of 3D Structural and Thermal Analyses
- Development Risks and Technology Gaps
- Recommended Risk Mitigation Plan
- Recommended Engine Demonstration Plan with Options
- Summary of Conclusions and Recommendations
- Agilis' Design and Testing Experiences with JT75/MT60
- Discussion
- Resumes of major contributors

Phase I/II Tasks and Deliverables

Phase I – Cycle Analysis and Design Feasibility evaluation

- Perform initial analysis of the engine cycle and evaluate approaches to mechanical/structural design and resulting producibility techniques.
- Identify advantages and/or limitations to the overall design, suggest relevant design enhancements and determine anticipated technology enabling issues to guide Phase 2.
- Work with LANL to identify potential commercial applications and perform initial analysis intended to determine optimum applications.

• Phase II – Technology Validation Program Development

- Conduct specific, limited analysis and/or sub-scale testing as required to provide information permitting continued pursuit of commercial applications fundings. Specific work performed will be determined jointly between Agilis and LANL at the conclusion of Phase I..
- Develop a Program Plan and Budget to define the Technology Validation Program for the SRTE concept which will take the technology demonstration to the level at which it could be transitioned into an engine development program.
- Support efforts to secure commercial application(s) funding.
- Create Technology Validation Program report.

• Deliverables

- Phase I: Assessment report on Cycle Analysis and design feasibility.
- Phase II: Technology Validation Program report.

Single Rotor Turbine Attributes

Advantages

- Power to volume ratio is very high
- Reduced number of parts
- Reduced length – very compact
- Reduced leakage paths
- Allows higher turbine inlet temperatures than un-cooled designs in small size engines* ($< 1 \text{ lbm/s}$ core flow)

Challenges

- Reduced wheel speed for given allowable stress levels
 - Necessitates increased stage count and/or loadings or lower cycle pressures
- Reduced Compressor Efficiency
- Reduce blade pull through thin wall manufacturing techniques.



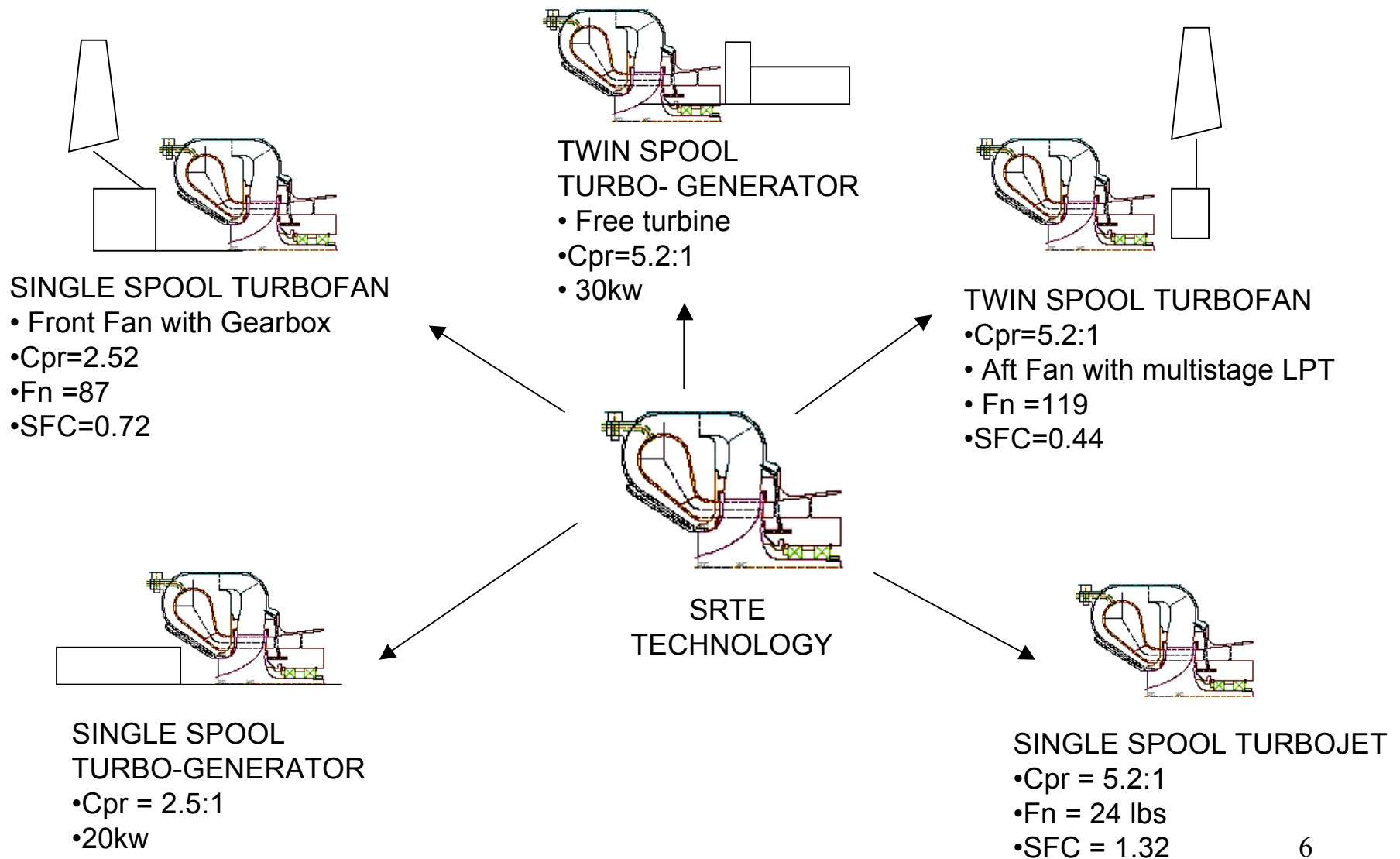
* In small sizes, conventionally cooled designs are impractical or impossible

Phase 2 Recommendations

(from Phase I Report)

- Complete design iteration process of a baseline design to better quantify the comparative performance measures and limitations, and to guide application selection
- Evaluate ultra-small gas turbine to exploit inherent cooling advantages of the SRT concept
- Perform limited 3D structural and thermal analyses
- Determine desired figures of merit for target applications
- Quantify attributes of optimized configuration
- Select preferred application and associated engine concept
- Determine technology gaps and plan to resolve gaps
- Assess development risks
- Develop risk mitigation plan
- Develop engine demonstration plan
- Propose engine demonstration plan to funding agencies

Candidate SRT Enabled Applications



Bench Marking Competitive Engines – Turbojets and Turboshfts

Industry Wide Search includes:

- ⇒ Unmanned Aerial Vehicles (UAVs')
- ⇒ Hobby industry

Models in the hobby industry include:

- ⇒ Wren Turbines (Gas Turbine Builders Association)

Models in the UAV industry include:

- ⇒ Microjet Engineering
- ⇒ Hamilton Sundstrand

State-of-art Turboshaft

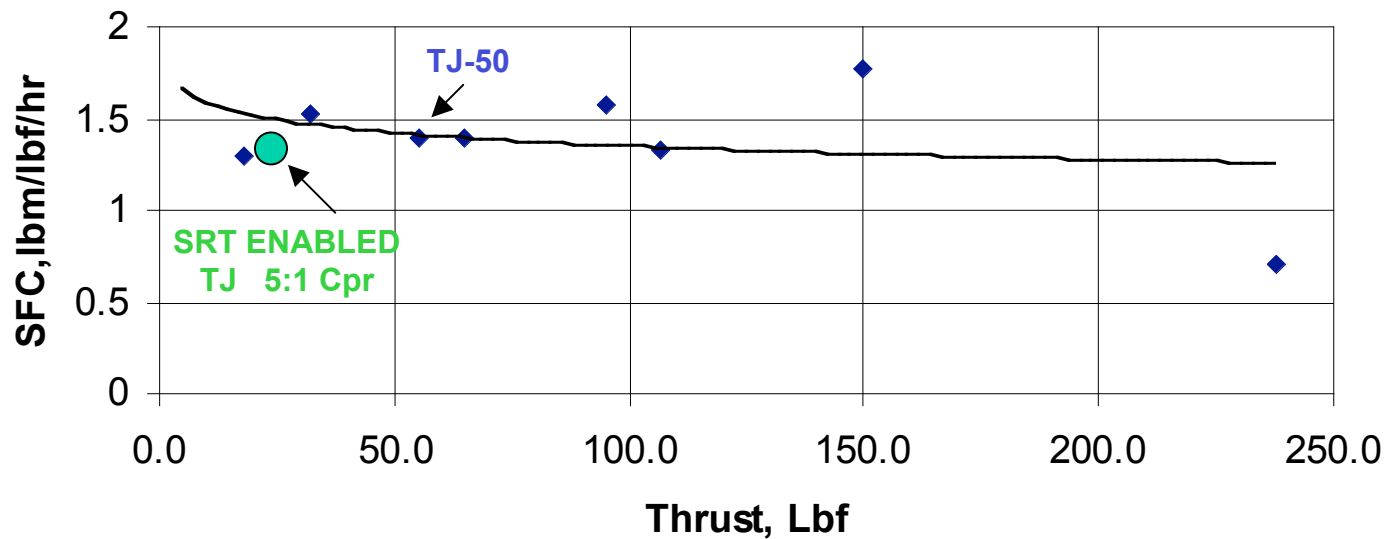
- ⇒ Jet Fuel Starters

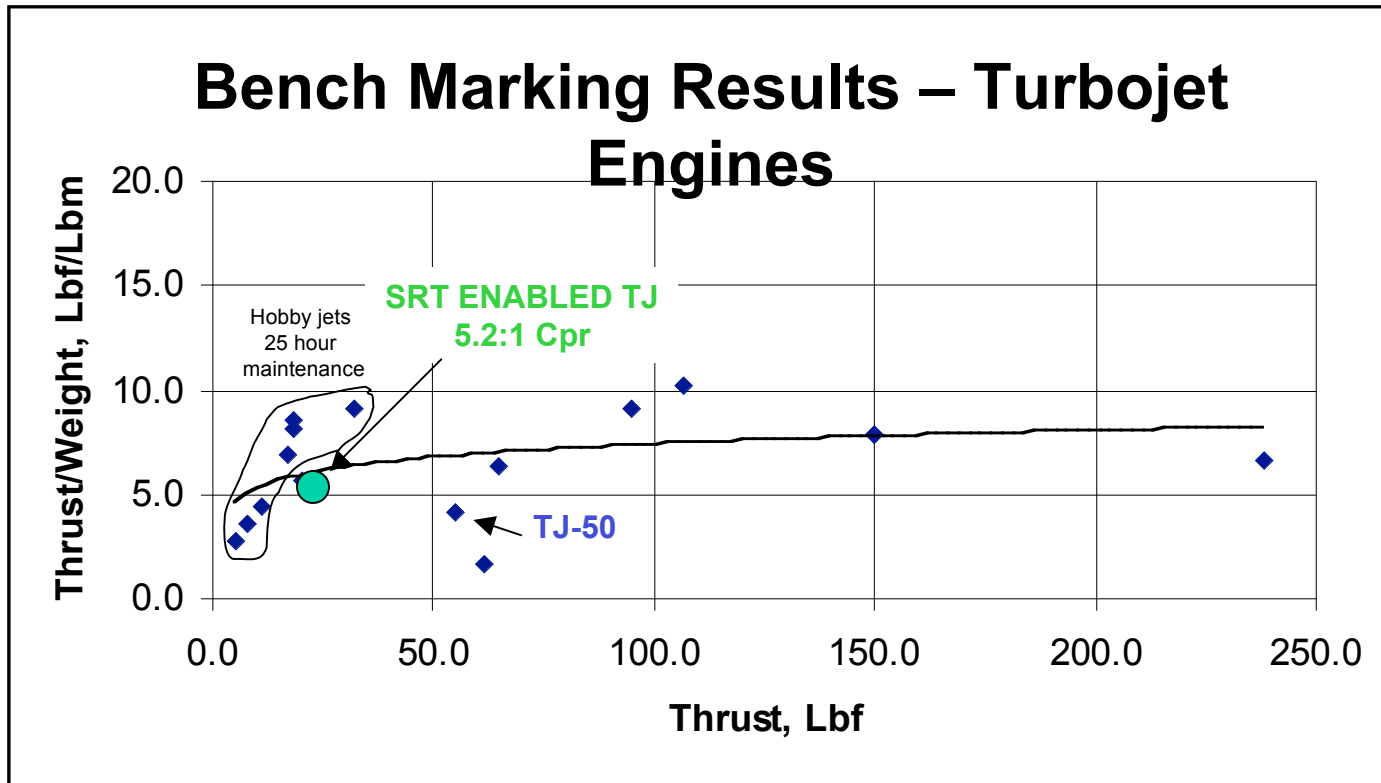
Ground Based Electrical Generators

- ⇒ Capstone MictoTurbine



Bench Marking Results – Turbojet Engines





Gas Turbine Bench Marking – Competitive Engines

Engine type / Model Number	Thrust or HP	Weight	HP/Wt or Fn/Wt	HP/Vol or Fn/Vol	SFC or BSFC	Major Components	Life
Power Generation:							
SRT ENABLED 20KW POWER CUBE	28	4.73	5.9	0.32	1.24	(3) SR+C+ACC	On condition
SRT ENABLED 20KW POWER CUBE (with gearbox)	28	11	2.5	0.1	1.24	(4) SR+C+GB+ACC	On condition
APU – APS500R	50	120	0.416	N/A	N/A	(6) CC+C+T+FT+GB+A CC	On condition
JET Fuel – JFS100	90	82	1.1	0.068	1.3	(6) CC+C+T+FT+GB+A CC	On condition
C330 Microturbine	42	225 with generator	0.2	0.005	0.86	(5) CC+C+T+ACC+ RECUPERATOR	5,000-8000 HR
Propulsion:							
SRT ENABLED TURBOJET (Pr=5.2:1)	24	4.73	5.07	.111	1.32	(3) SR+C+ACC	On condition
JSF100 (Jet Version)	100	55	1.8	0.10	1.37	(4) CC+C+T+ACC	On condition
TJ-50 (with 1 KW Alternator)	55	13.2	4.1	.123	1.4	(4) CC+C+T+ACC	>40 min
HF30 (kit engine)	32	3.5	9.1	0.27	1.5	(4) CC+C+T+ACC	25 hrs

Gas Turbine Bench Marking – Competitive Engines

<div> <div>Relative Comparison</div> <div> <div>Engine Type / Model Number</div> <div>↓</div> </div> <div>→</div> </div>	Normalized Mfg Cost*	Normalized Operating costs**	HP/Wt or Fn/Wt	HP/Vol or FN/Vol	SFC or BSFC	Life
Power Generations:						
SRT Enabled 20KW Power Cube (with gearbox)	Base	Base	Base	Base	Base	Base
APU – APS500R	+50%	+50%	-83%	-	-	Base
JET Fuel Starter – JFS100	+50%	+65%	-56%	-32%	+5%	Base
SRT Enabled 20KW Power Cube (no gearbox)	Base	Base	Base	Base	Base	Base
Microturbine - C330	+66%	-24%	-97%	-98%	-30%	Base
Propulsion:						
SRT Enabled Turbojet (Pr=5.2:1)	Base	Base	Base	Base	Base	Base
JFS100 (jet version)	+33%	+49%	-65%	-10%	+4%	Base
TJ-50	+45%	+63%	-19%	+11%	+6%	Less
HF30 (kit engine)	-	-	+79%	+143%	+13%	Less

Notes:

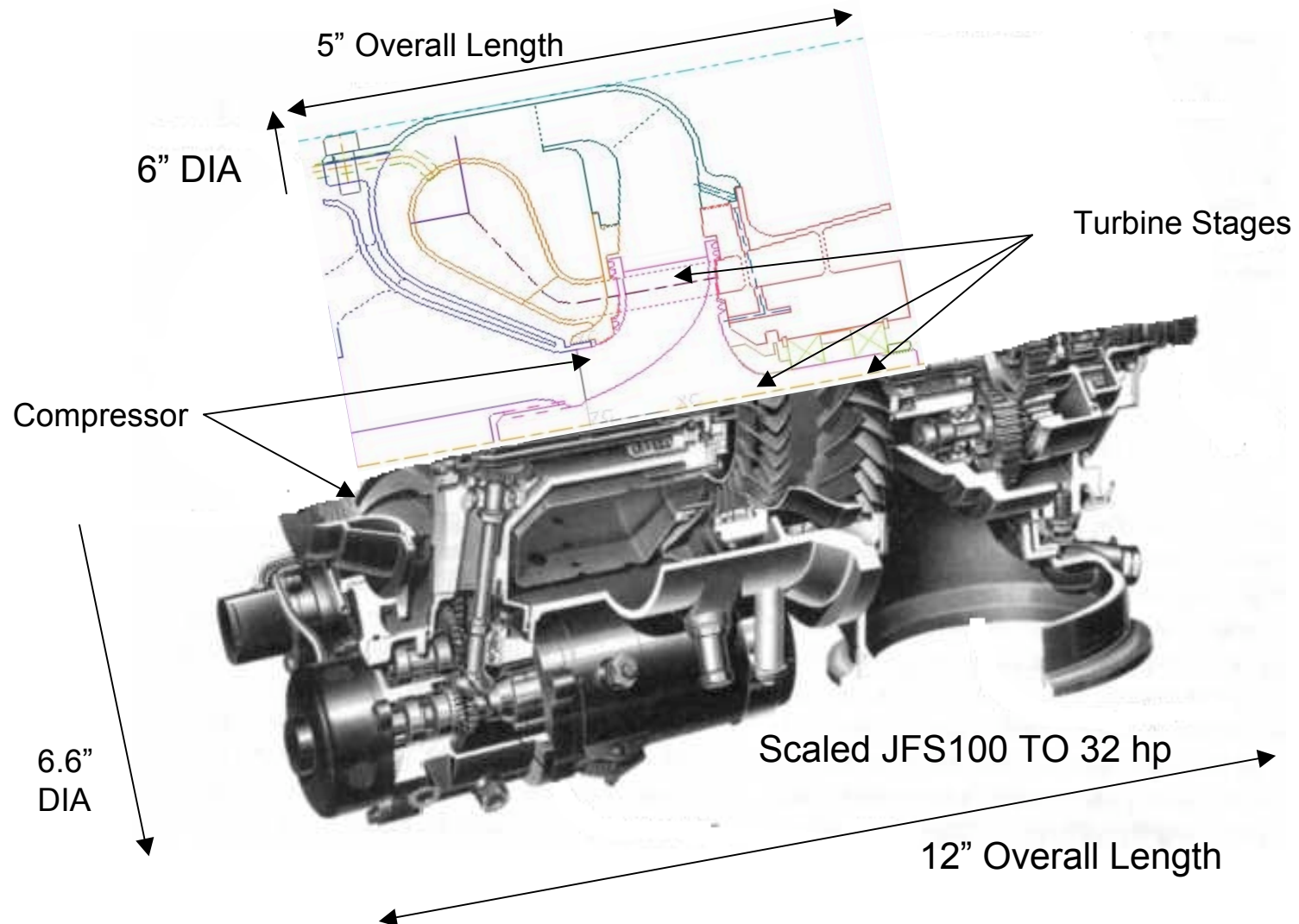
* = function of number of Major Components

**Calculated as 3 x Fuel Cost + Mfg Cost

Jet Fuel Starter Physical and Functional Comparison - SRT Enabled Power Cube and APU

	Allied Signal JSF 100-13	SCALED JSF 100-13	SRT Enabled 20KW Power Cube (no G/B)	SRT Enabled 20KW Power Cube (with G/B)
WAT	1.6	0.57	0.33	0.33
HP	90	28	28	28
N1- RPM	72,500	130000	124,000	124,000
CET F	1850	1850	2200	2200
N2 - RPM	60,400	108000	124,000	124,000
OUTPUT RPM	3,000	5400	124,000	6,200
LENGTH	22	12	5	10
HEIGHT / WIDTH	12	6.6	6	6
FUEL CONSUMPTION	1.3lb/shp-hr	1.3lb/shp-hr	1.24lb/shp-hr	1.24lb/shp-hr
CONFIGURATION	1C-1A-1FT	1C-1A-1FT	1C-1A	1C-1A
WEIGHT	82	25	5	11
HP / VOLUME INCH**3	0.068	0.068	0.32	0.1
POWER DENSITY		Base		1.46

SRT Enabled 20 KW Power Cube is Compact Relative to Conventional Design



Selected Baseline SRT Enabled Application Power Cube

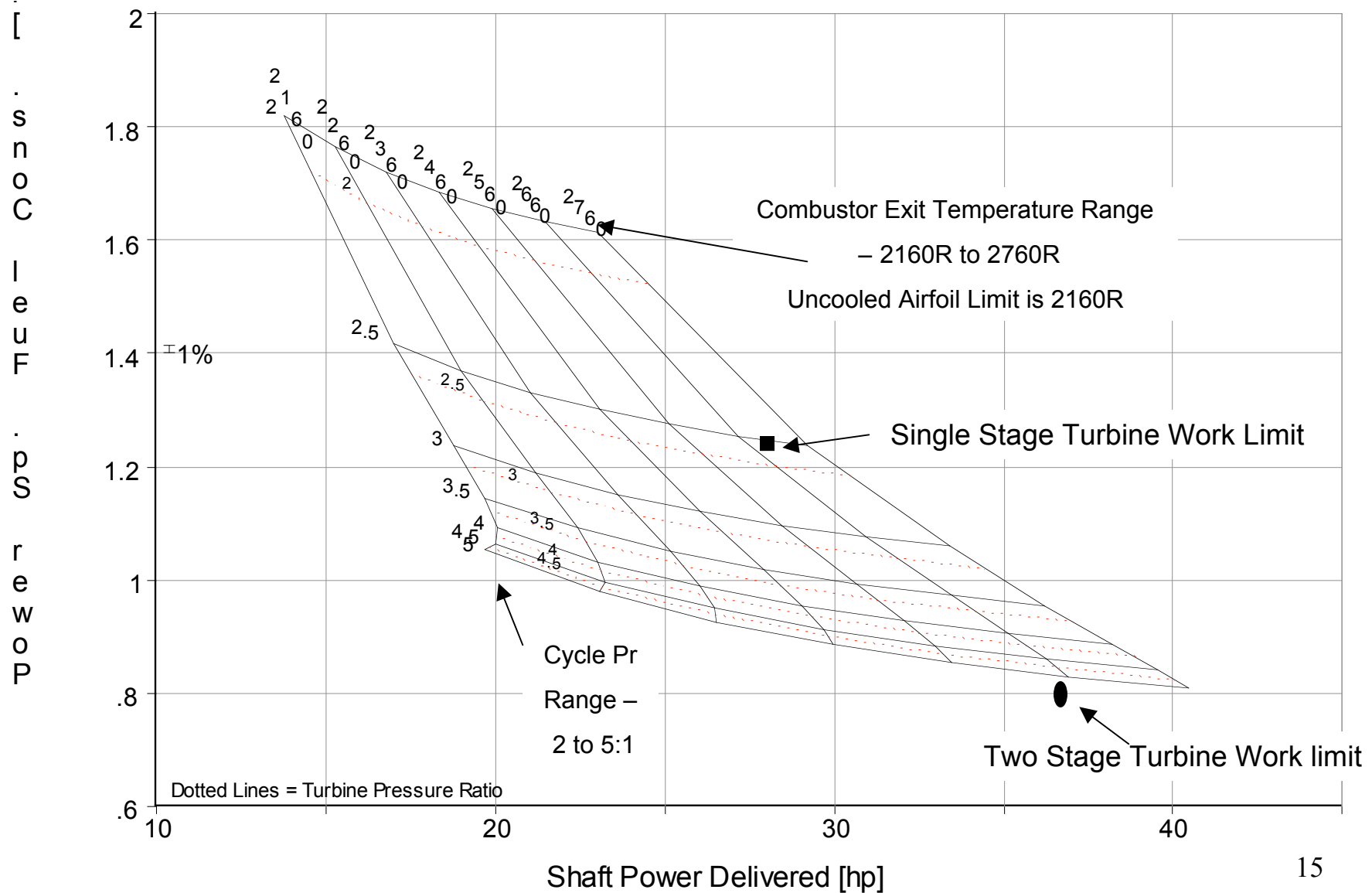
APPROACH:

- Baseline the 20KW turbo-generator (Power Cube)
- Exploit power density advantages
- Mature mechanical design
- Establish mechanical design based on cycle studies
- Identify technology gaps
- Define development program

STATED REQUIREMENTS:

- Output: 10-20 KW
- Physical size: no greater than 6" X 6" X 6"

Turboshaft Engine Parametric Study



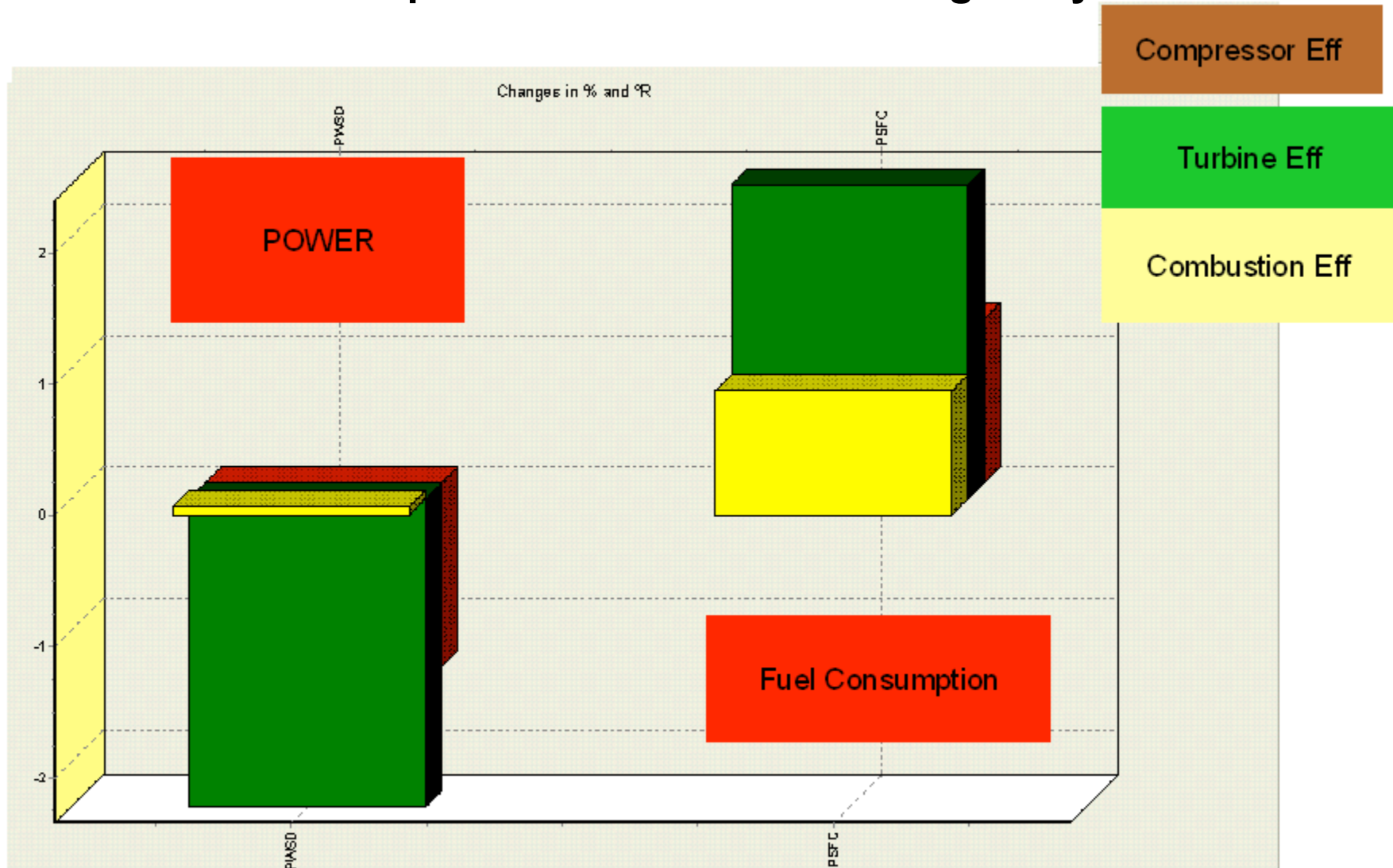
Baseline Study Engine Cycle

- Single Spool 20 KW Power Cube

Air Flow	0.33 lbm/sec
Fuel Flow	0.00955 lbm/sec
Power	20 KW / 28 HP
PSFC	1.24 lbm/hp/hr
Pr	2.517
Combustor Exit Temp	2694 deg. R / 2234 deg. F
Turbine Metal Temp	2000 deg. R / 1540 deg. F
Eff-Comp	0.72
Eff-Turb	0.80
Combustor Pressure Drop	3%
Overboard Leakage	5%
Fuel Heating value	18,600 Btu/lbm (Jet Fuel)
RPM	124,000

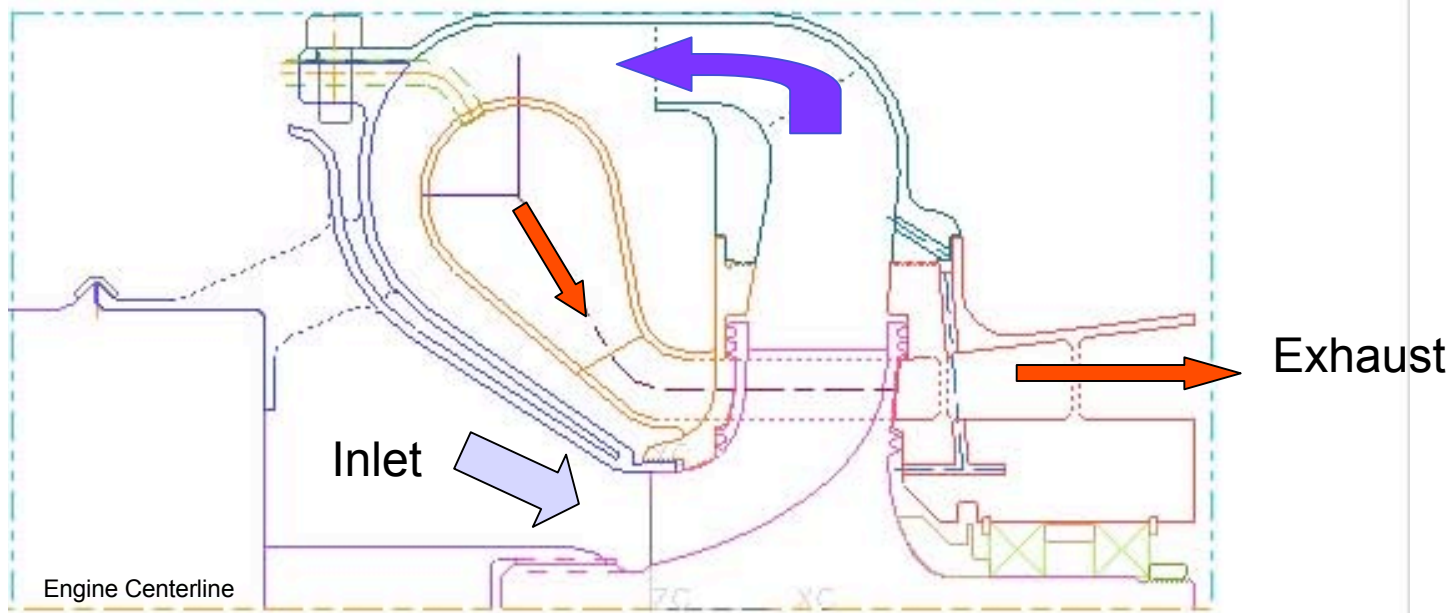
Effects of Component Efficiencies on Power and Fuel Consumption

- Turbine performance dominates engine cycle



Baseline Turbomachinery Arrangement

- RESULTS IN A SHORT COMPACT ENGINE
- High Power to Density Ratio



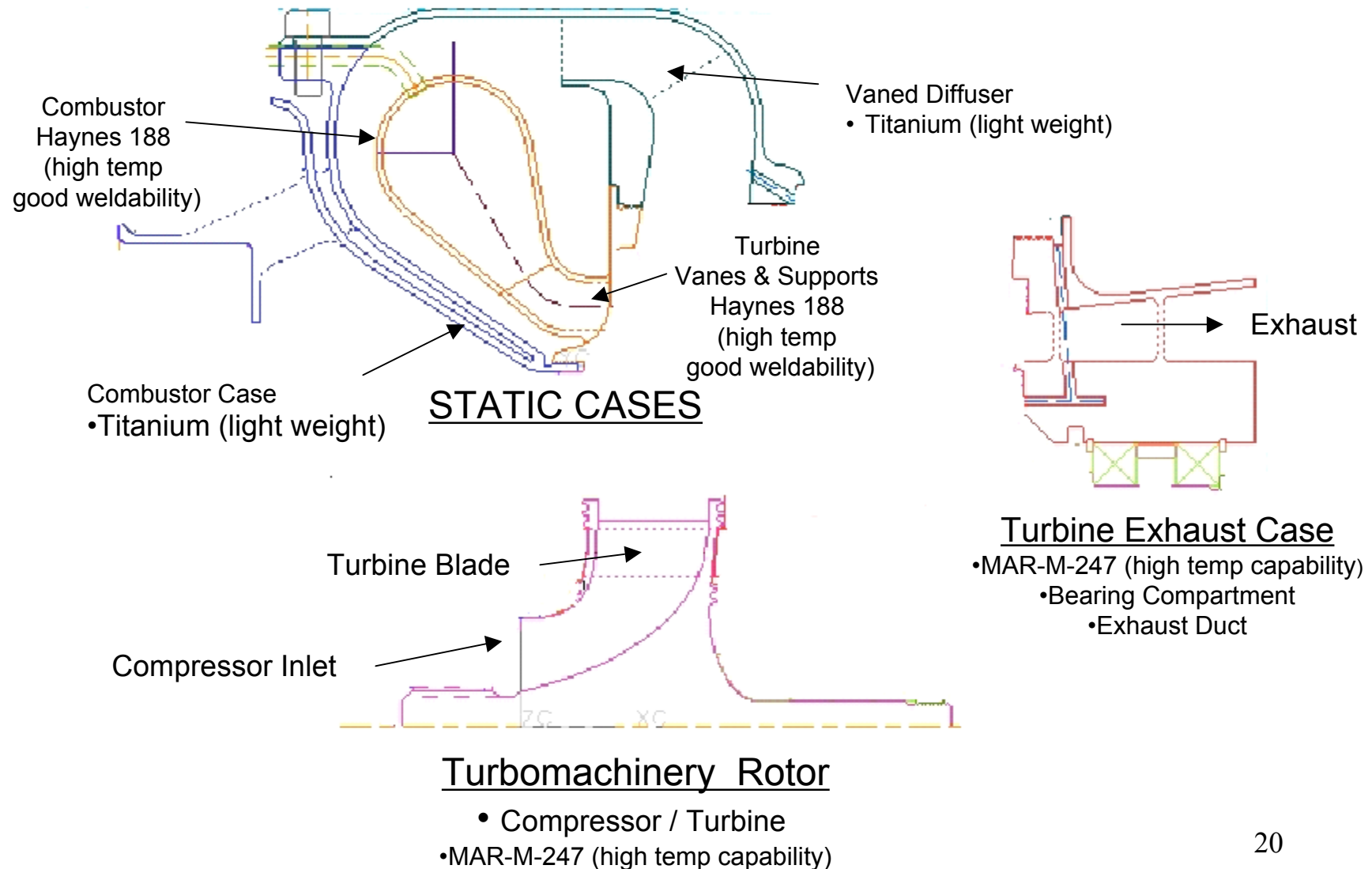
Weight Estimate

Baseline SRT Enables Power Cube

(Exclusive of PMG)

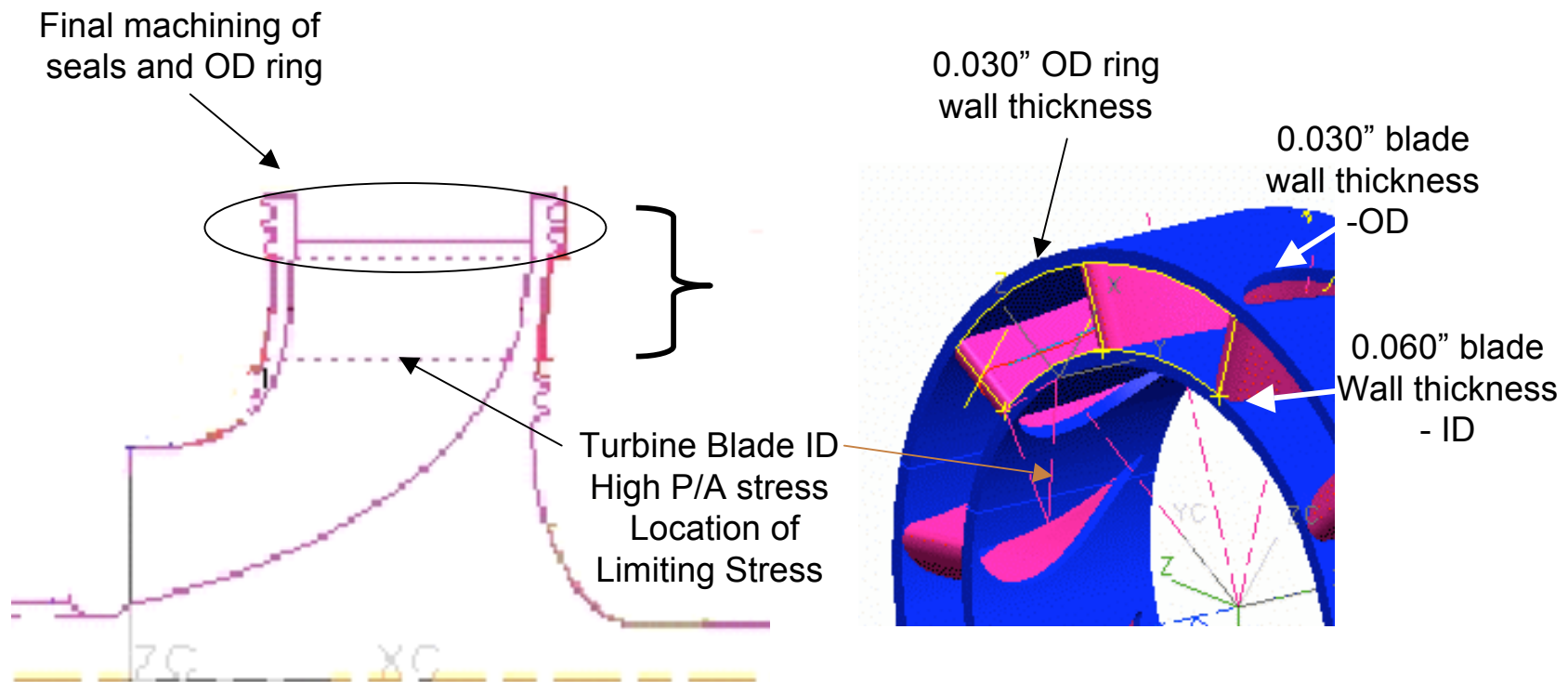
Component	weight lbs
Rotor	0.858
Turbine Exhaust Case	0.77
Combustor / Vane	0.57
Outer Diffuser	0.59
Inner Diffuser and Generator Mount	0.62
Externals, Controls and Misc	<u>1.5</u>
Total Weight	4.73

SRT Enabled 20KW Power Cube is Composed of Only 3 Modules

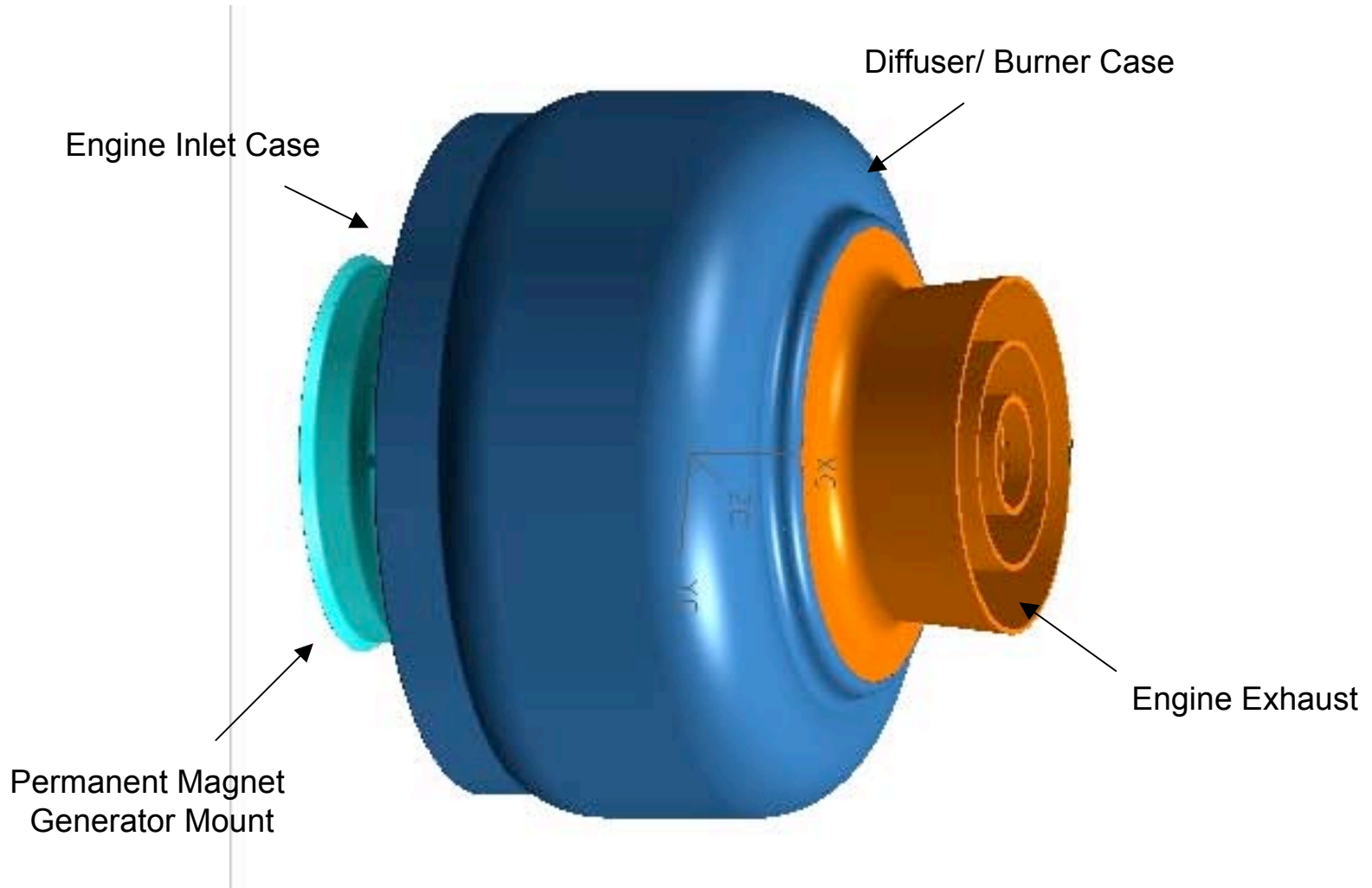


Structural Analysis Indicate Rotor Will Require High Temperature Materials and Thin Wall Technology

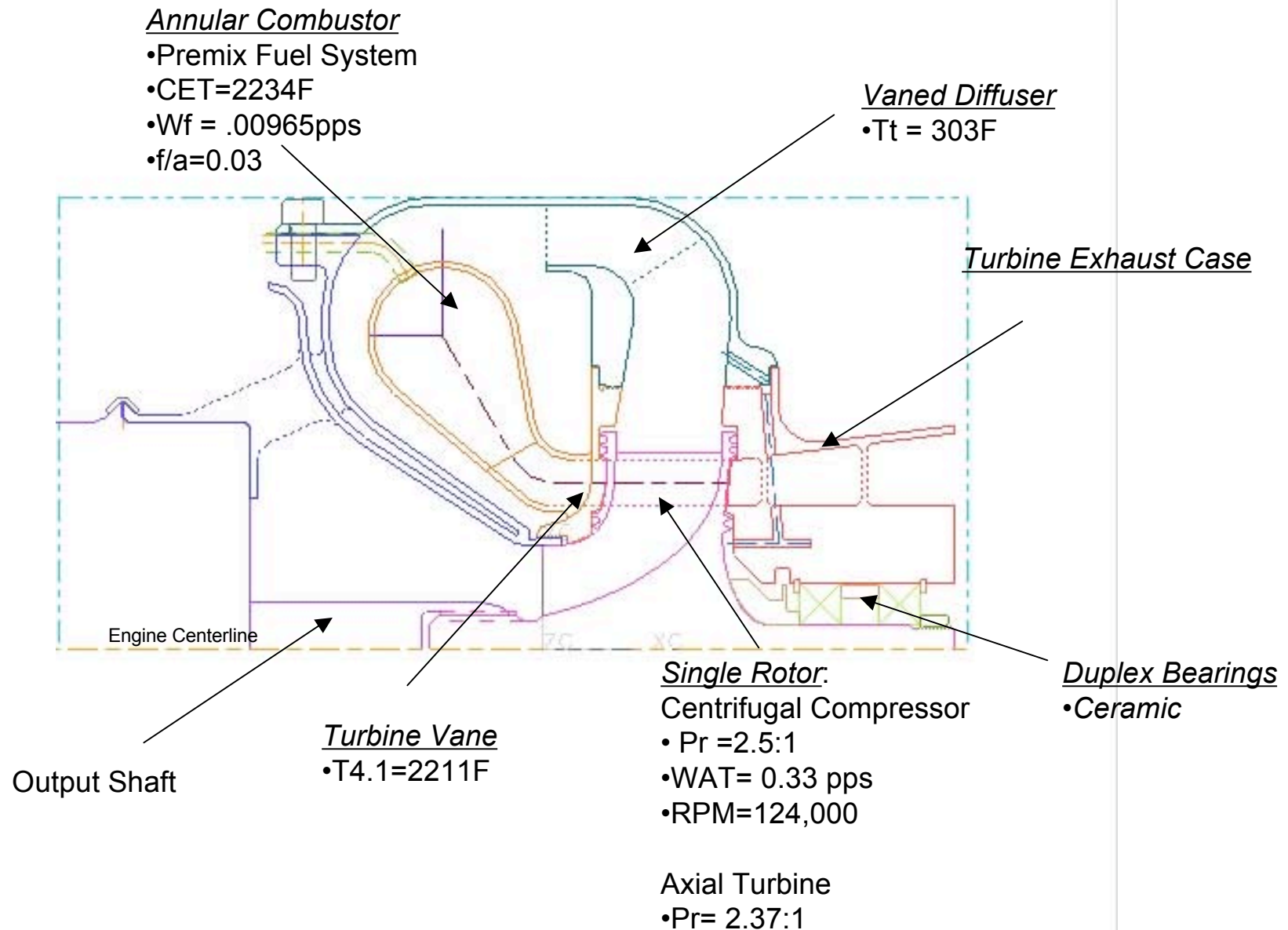
- MAR-M-247 for stress rupture at high temperatures
- Tapered turbine airfoil walls (0.060 to 0.030") for reduced pull
- Reduce OD ring thickness to 0.030" for reduced pull



SRT Enabled 20 KW Power Cube Side View



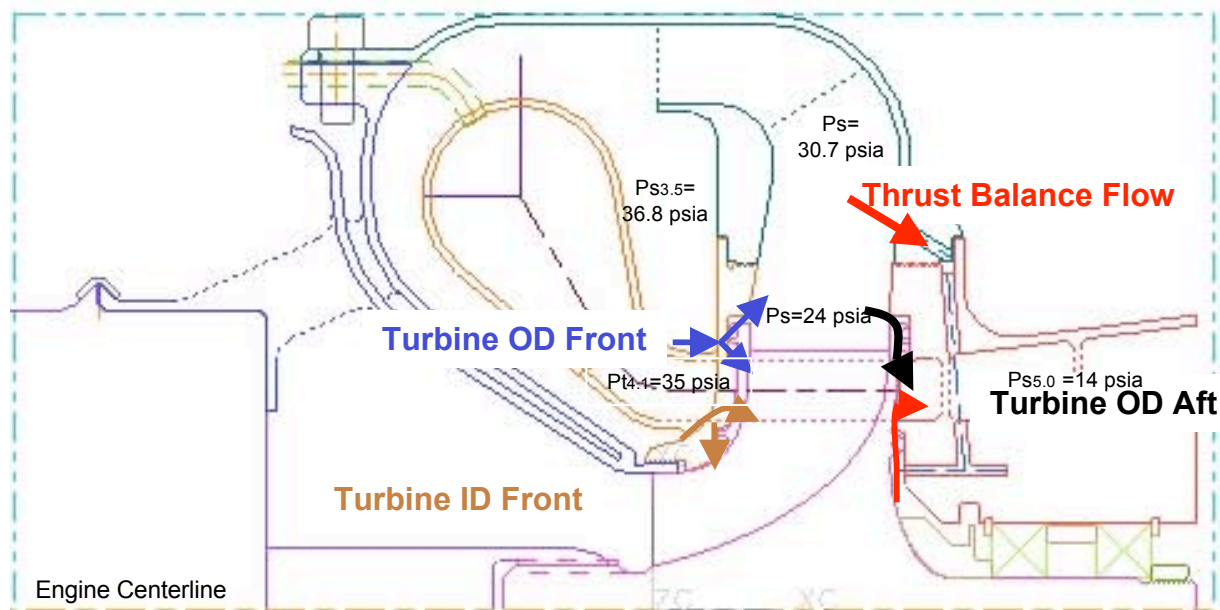
Baseline Engine Features and Cycle Definition



Secondary Flow Schematic for SRT Enabled Power Cube

Reduced leakage areas compared with conventional designs improved performance

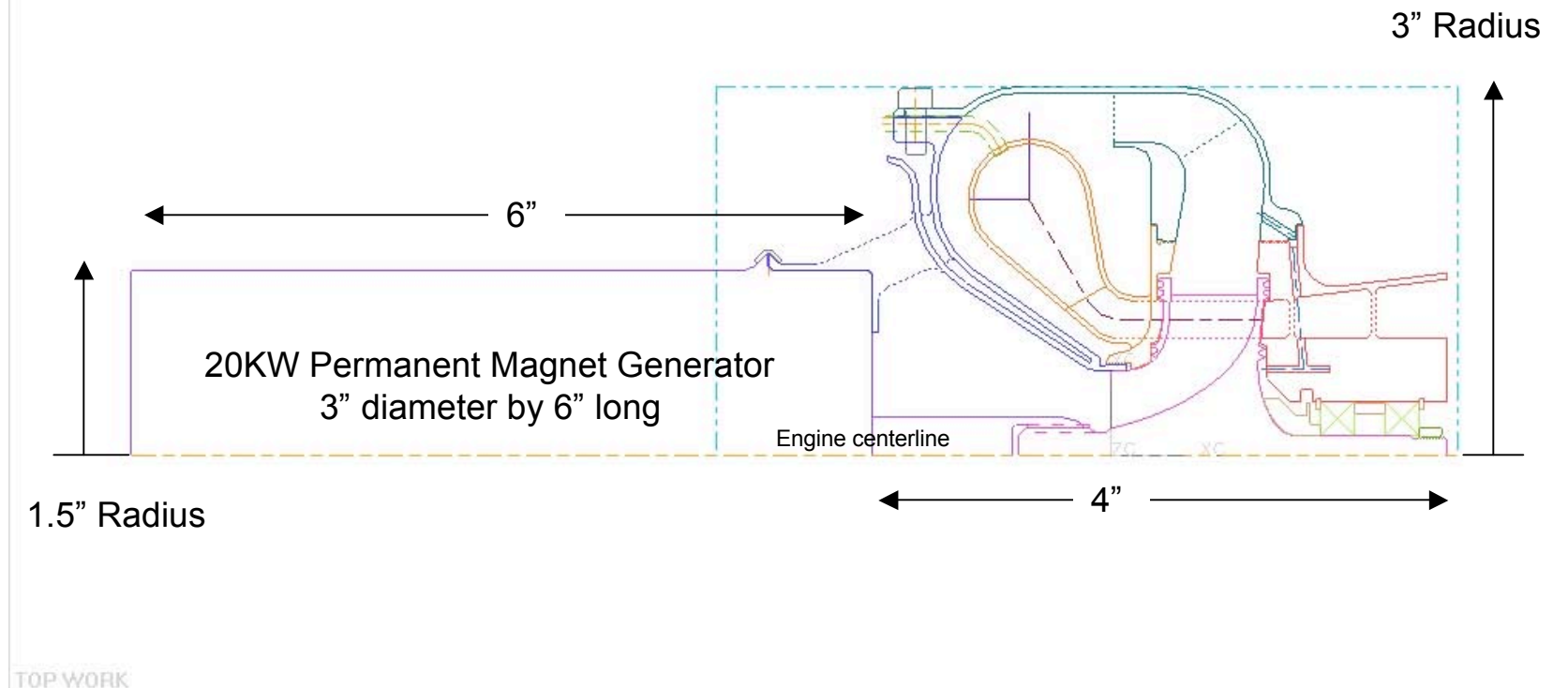
- Only 4 main leak areas: front and rear of turbine blade vs 6 for conventional design
- No bore flow needed around turbine rotor
- No TOBI needed for blade cooling (required swirl provided by HPC)



Gas Generator and Permanent Magnet Generator Sizes Meet Requirements

- Volume of Engine and Generator less than 6"X6"X6" Package Requirement (216 in³)

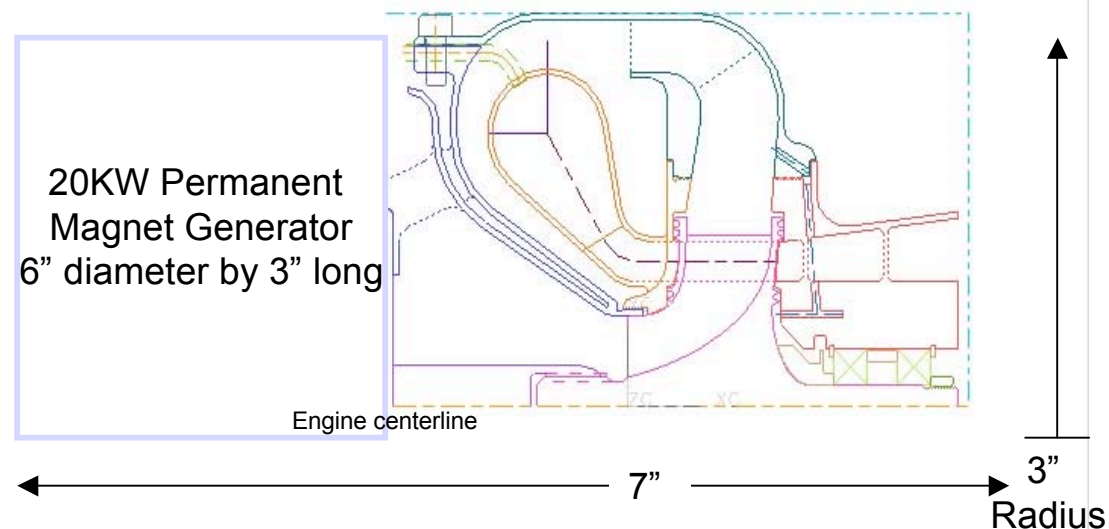
- Generator Vol = 42.4 in³
- Turbomachinery Vol = 101 in³
- Accessories and Controls Vol = 30 in³
- Total vol = 173.4 in³



Gas Generator and Permanent Magnet Generator Sizes Meet Requirements

Alternate Generator Design / Higher Risk Design

- Volume of Engine and Generator less than 6"X6"X6" Package Requirement (216 in³)
 - Generator Vol = 85 in³
 - Turbomachinery Vol = 101 in³
 - Accessories and Controls Vol = 30 in³
 - Total vol = 216 in³



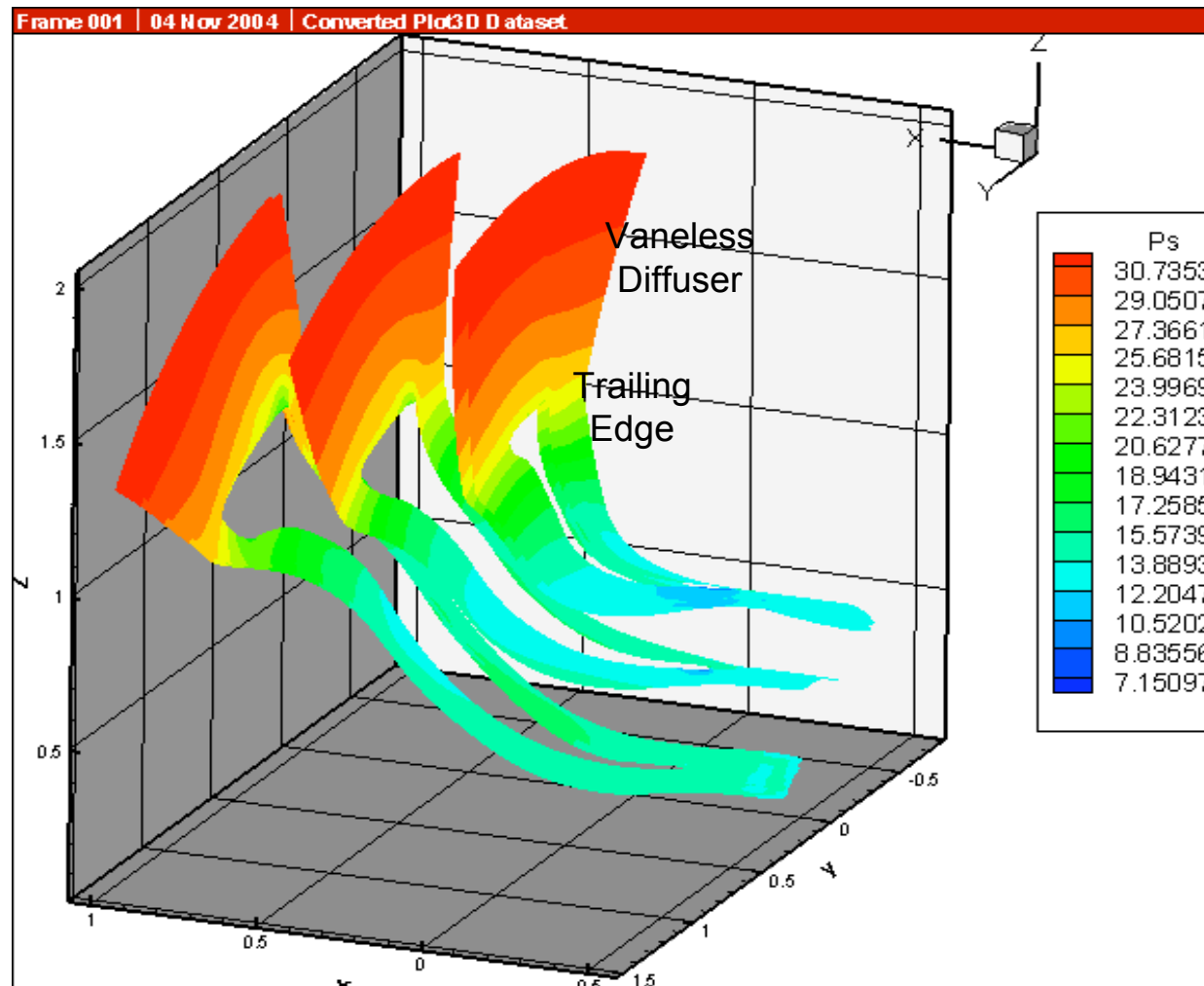
Component Performance Analysis- Centrifugal Compressor

Airflow	0.33 lbm/sec
RPM	124000. rpm
Tip Speed	1350 ft/sec
Specific Speed	123 rpm-ft^{.75}/sec^{.5}
Exducer Backsweep	25 deg.
Efficiency	72%
Stall Margin	15%
No. Impeller Blades	10
No. Diffuser Vanes	29
Diffuser Inlet Mn	0.95
Diffuser Vane LE MN	0.59
Diffuser Vane Le Radius/ Impeller Tip Radius	1.4
Diffuser Exit Mn	0.2

Increased Axial Depth at exducer to compensate for blockage; rotating vaneless space to mitigate mixing losses

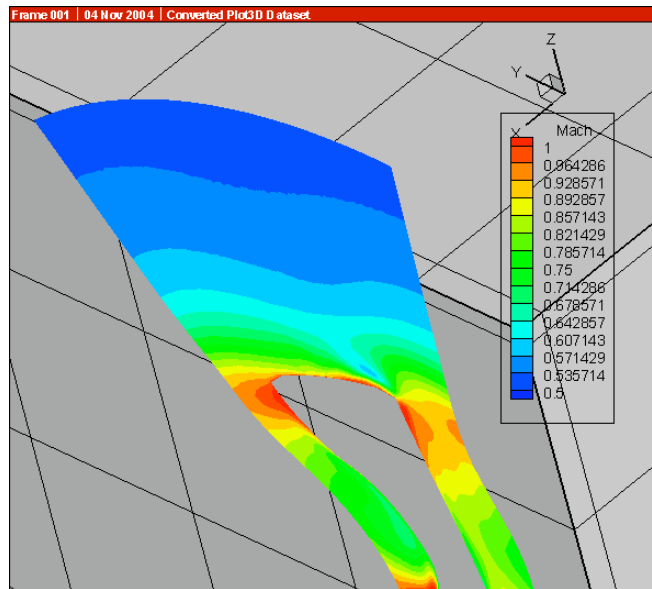


CFD Streamline Static Pressure Distribution



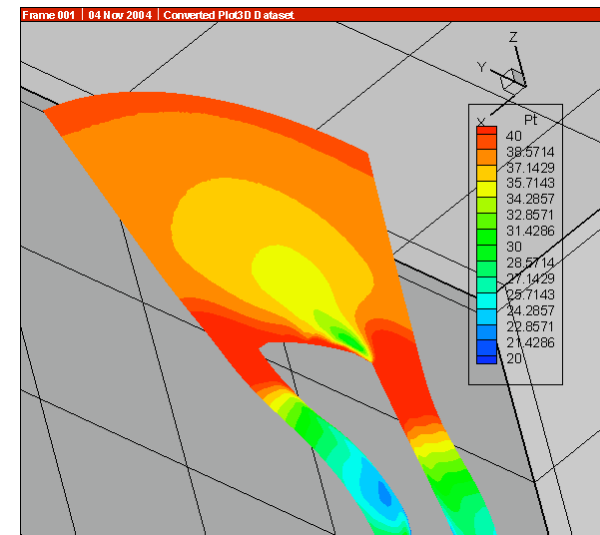
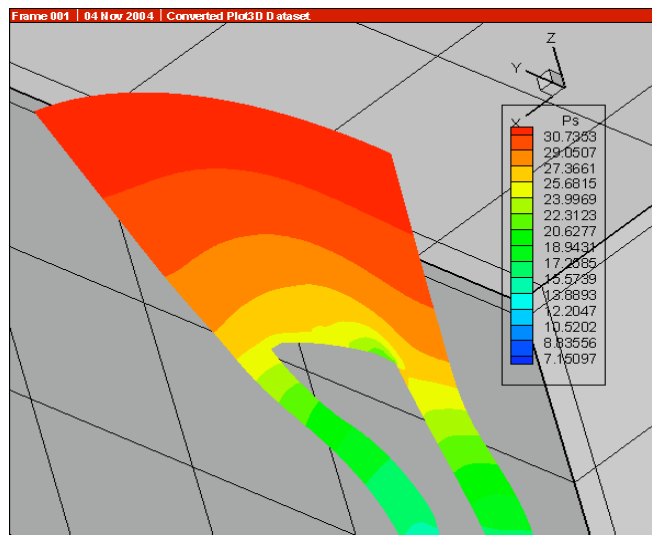


Mach Number



Contours (in Absolute Frame of Reference)
Near Impeller Trailing Edge

Static Pressure



Total Pressure

Component Performance Analysis - Combustor

Average Mn	0.043
Residence Time	1.4 msec
Fuel Flow Rate	0.0097 lbm/sec
Fuel Heating Value	18,600 BTU/lbm
Pressure Drop	3%
Combustor Efficiency	99%
Inlet Temperature	764 deg. R
Outlet Temperature	2694 deg. R

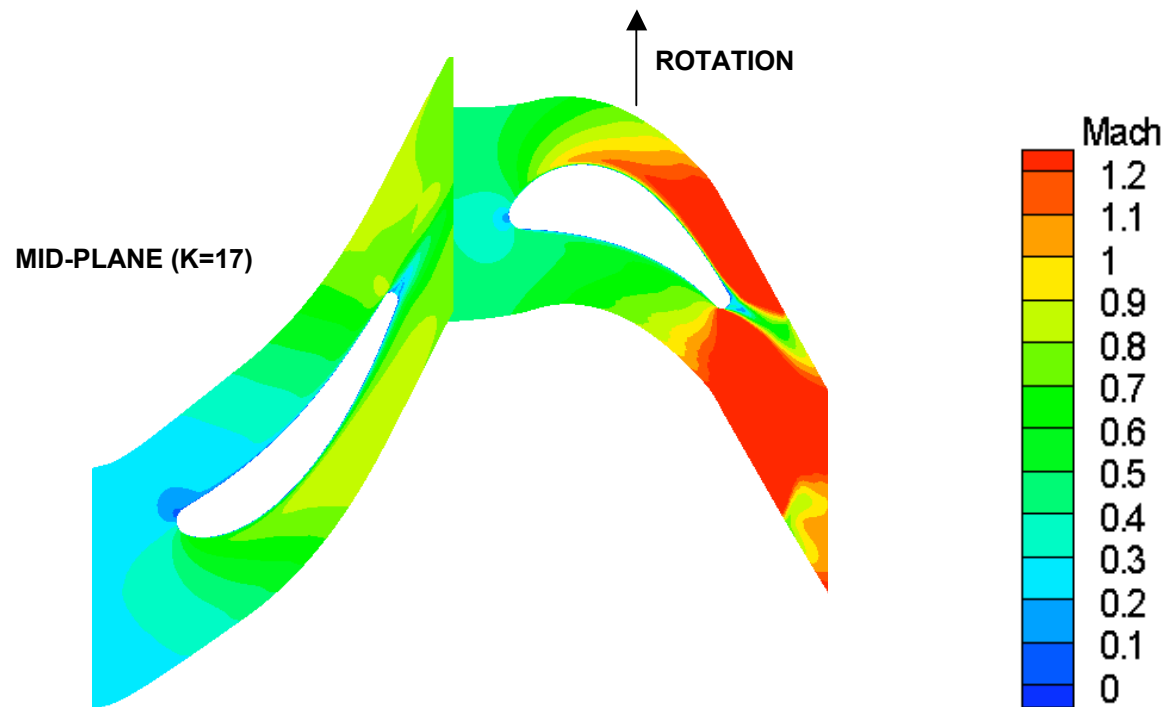
Component Performance Analysis - Turbine

Conventional Axial Flow Turbine in Small Size

EXPANSION RATIO	2.36
RPM	124000.
REACTION	0.55
FLOW COEFFICIENT (C_x/U)	0.71
FLOW PARAMETER ($W \cdot \sqrt{RT}/P$)	3.34
WORK COEFFICIENT ($gJ\Delta H/U^{**2}$)	1.88
VELOCITY RATIO (U/C)	0.52
ZWEIFEL COEFFICIENT (Vane)	0.83
ZWEIFEL COEFFICIENT (Blade)	1.02
EFFICIENCY (%)	80.0

CFD Relative Mach Number Contours

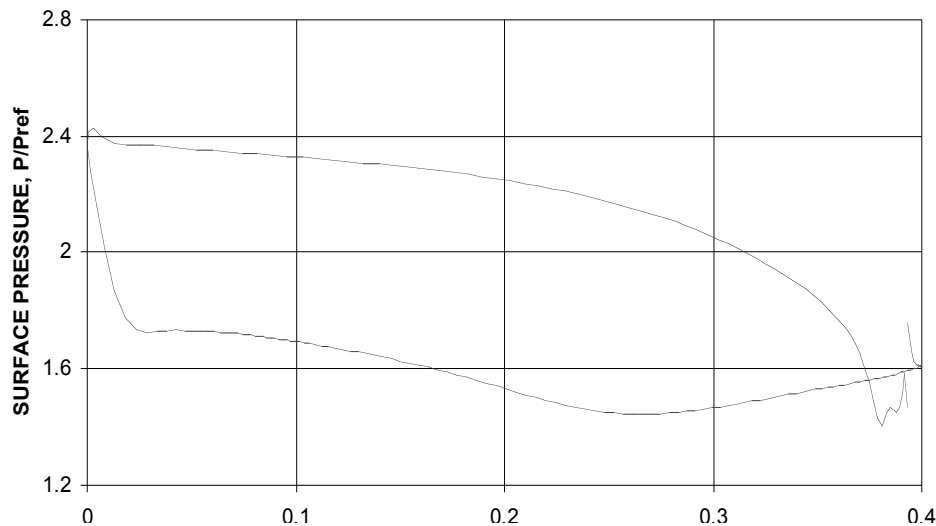
Aerodynamic flow field is well behaved



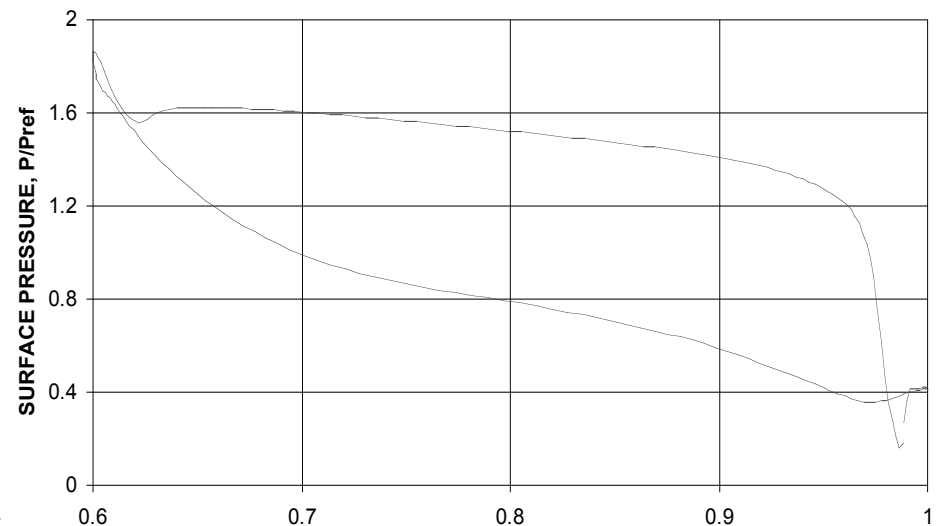
CFD Surface Pressure Distributions (Mid-Plane)

Aerodynamic flow field is well behaved

VANE



BLADE



Recommended Single Rotor Turbine Demo Technology Maturation Plan Options:

Current "State-of-the-Art"	Near Term Recommended Activities	Recommended Technology Program	Technology Program Objectives	Priority
Current blades flow 6-9% WAE vs 100% for SRT concept	Continue CFD on airfoils	Turbine airfoil heat transfer rig / Compressor Efficiency	Maintain acceptable metal temperatures with low pressure loss in cooling passage while meeting compressor goal efficiency	1
knife edge seals / brush seals	Continue conceptual design	High speed / high temperature compliant seals -	Demonstrate high speed / high temperature compliant seals -	2
Conventional casting capabilities	Refine rotor design and requirements	Demonstrate thin wall & high strength fabrication. Work with casting vendors	Full speed rotor capability for high power density	3
foil air bearings/ 400F temperature limit & ball thrust bearings	Continue conceptual design to quantify loads	Demonstrate high temp foil air bearings and thrust load modulation – Team with industry leaders in this field	Full life bearings at elevated temperatures	4

Recommended SRT Technology Maturation and Risk Reduction Programs

Turbine Airfoil Internal airflow model (priority #1)

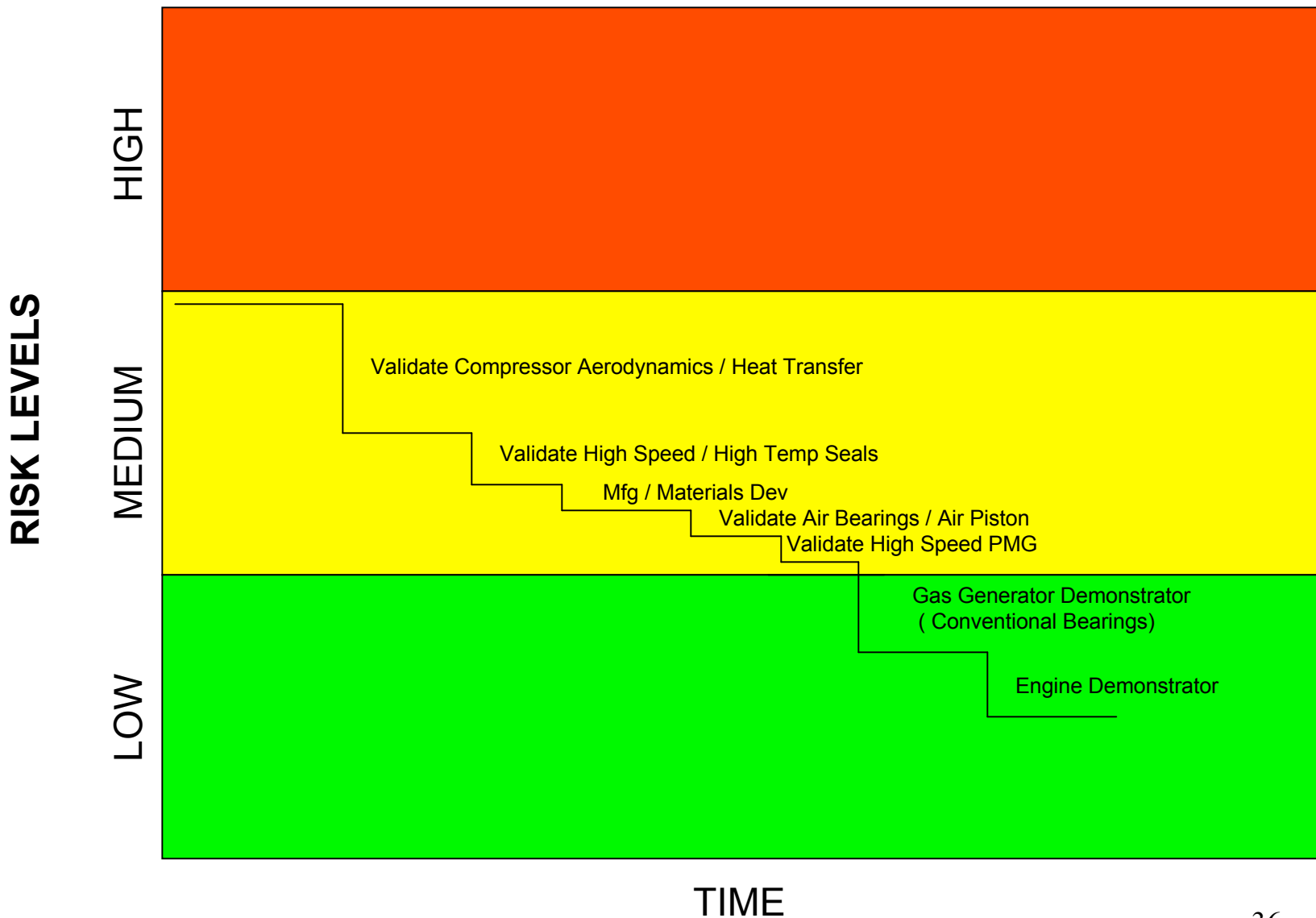
- Single airfoil passage model with airflow measurements
- Heat transfer measurements – thermal paint
- Validate internal aerodynamics / cooling capabilities
- Validate turbine and compressor efficiency
- Compare results with analytical models (CFD)

High Speed / High Temperature Seal Demonstration (Alternate)

- Evaluate candidate seal concepts
 - Knife edge seals
 - Face seals
 - Ceramic / Ceramic options



Risk Reduction Waterfall Chart

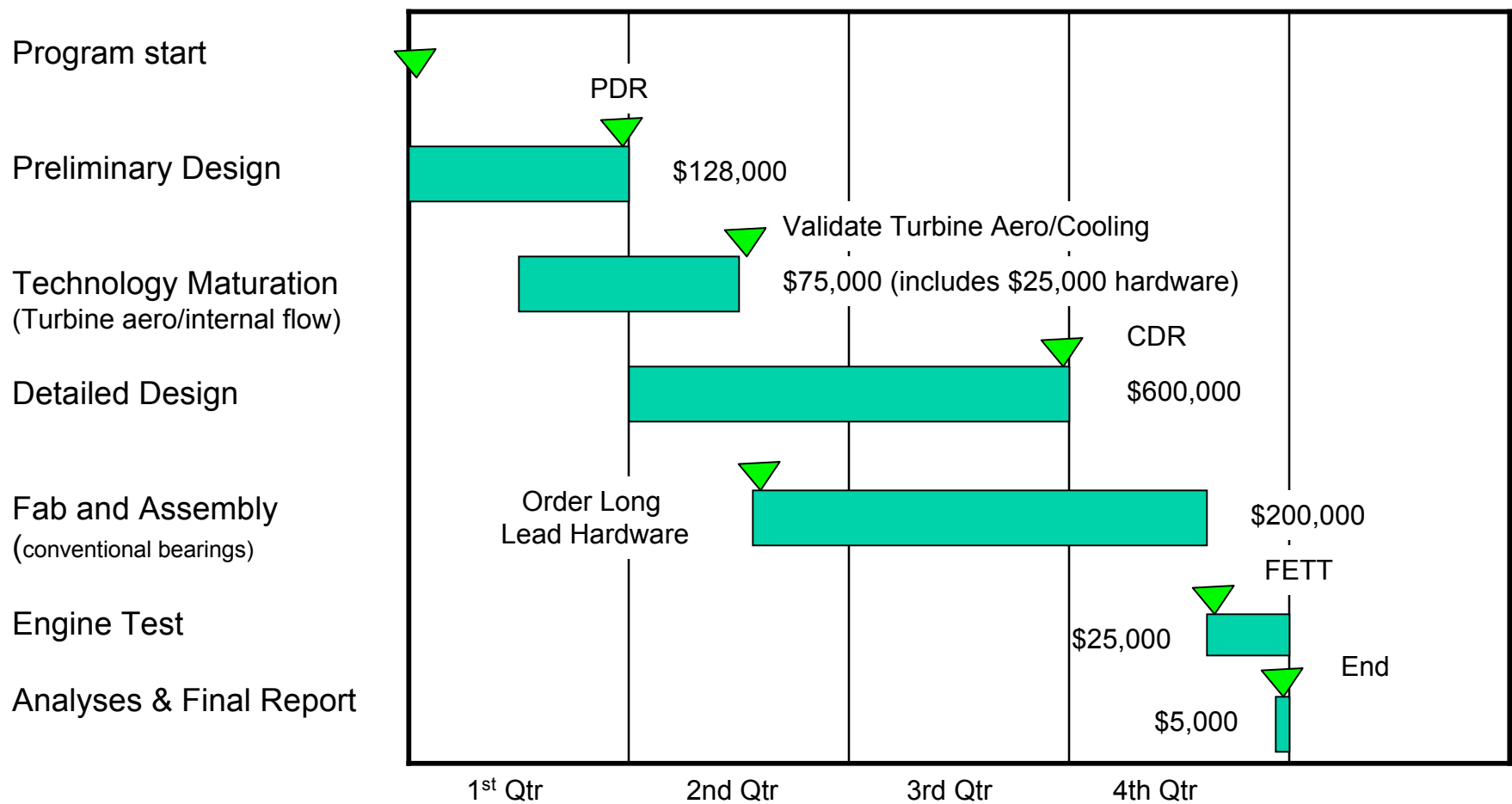


Single Rotor Turbine Enabled Power Cube Demonstrator Objectives:

- Transition SRT concept into an engine development program
 - Build running prototype
 - Obtain meaningful test data
- Demonstrate marketable advantages
 - Attain high power density (25 - 50% improvement)
 - Validate flow path efficiency
 - Prove turbine cooling effectiveness
 - Design for manufacturability
 - Meet size requirement
 - Produce 10 – 20KW power

Proof of Concept

SRT Enabled Power Cube Proof of Concept Development Plan (\$1.03M)

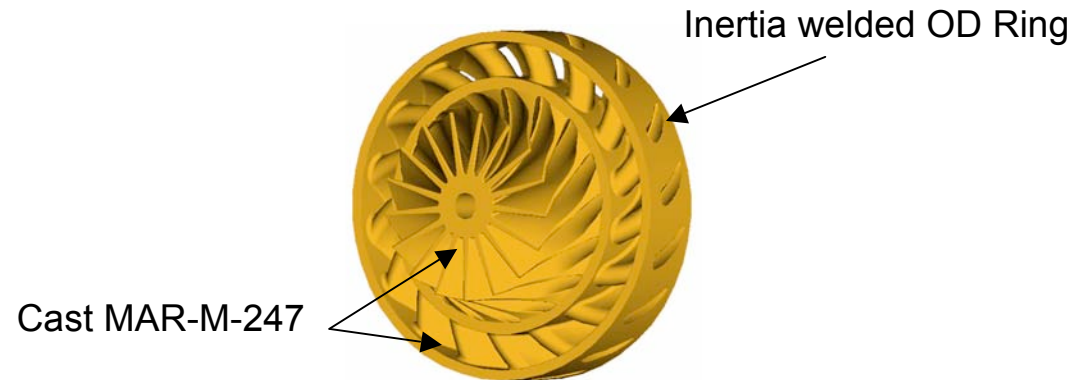


Single Rotor Design Options



PRIMARY ROTOR APPROACH

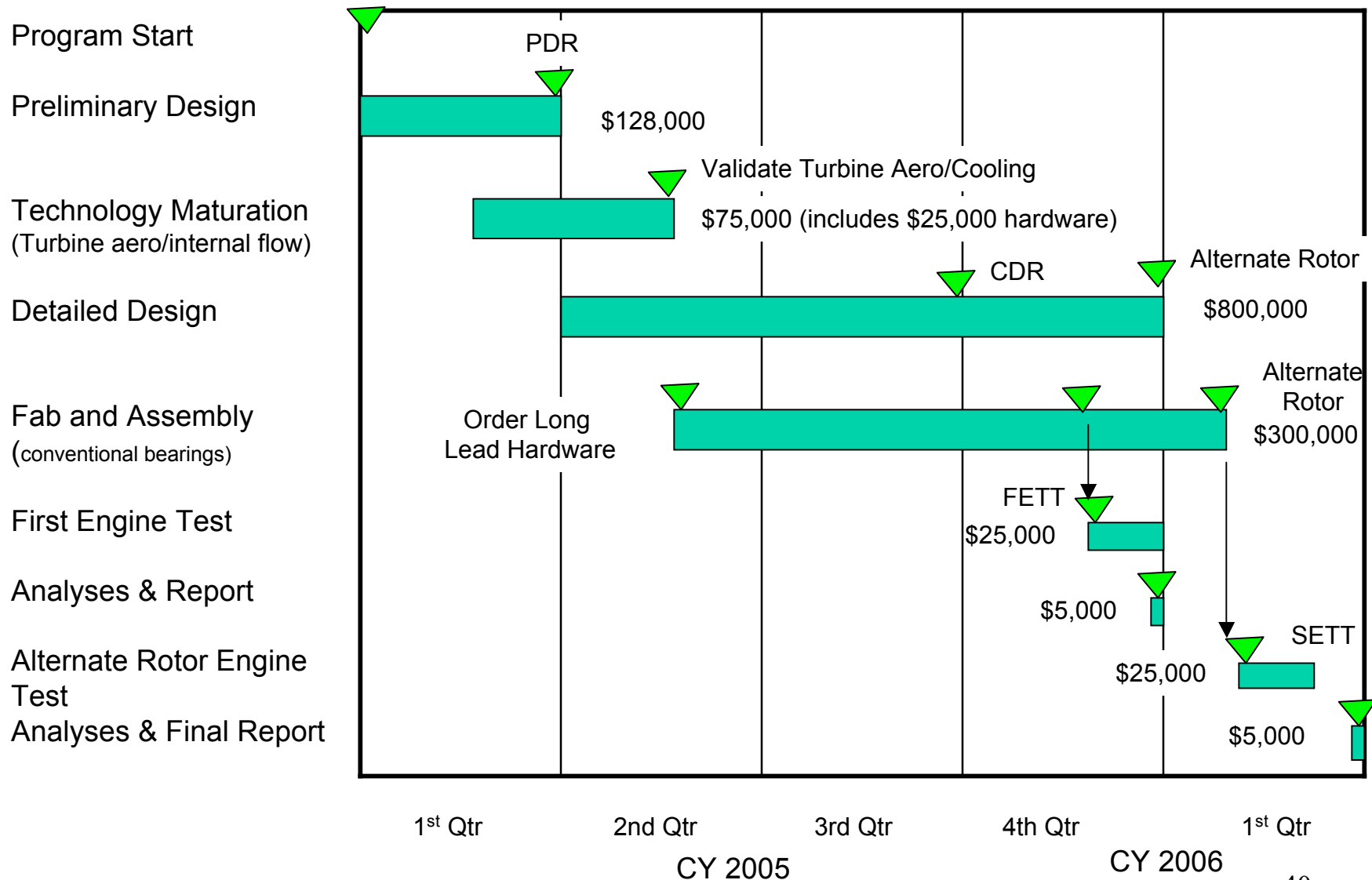
- Cast MAR-M-247 for stress rupture at high temperatures
- Tapered turbine airfoil walls (0.060 to 0.030") for reduced pull
- Reduce OD ring thickness to 0.030" or less for reduced pull



ALTERNATE ROTOR APPROACH

- Cast MAR-M-247 compressor and turbine airfoils
- Inertia welded OD ring and seal package
- TBC on airfoils and rings
- Tapered turbine airfoil walls (0.060 to 0.030") for reduced pull
- Reduce OD ring thickness to 0.030" or less for reduced pull

SRT Enabled Power Cube Proof-of-Concept Alternate Development Plan (\$1.36M)



Phase 2 Conclusions and Recommendations

- Preliminary analysis indicates SRTE concept is feasible and usable in numerous applications
 - Challenges but no “show stoppers”
- SRT concept offers significant power density improvements over conventional un-cooled gas turbines
- SRT enabled power cube offers the biggest payoff
- Single spool turbojet attractive from SFC and thrust/weight
- Agilis Engineering, Inc. ready for Proof-of-Concept Program to demonstrate concept
- Agilis has Design and Testing Experience with Small Gas Turbines – Can bring engine testing facilities to program

DISCUSSIONS